Some limitations and principles of nanosecond time measurement in nuclear physics

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SESSION I.1

SOME LIMITATIONS AND PRINCIPLES OF NANOSECOND TIME MEASUREMENT IN NUCLEAR PHYSICS

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1. Introduction

Already before the second world war extensive use was made of *microsecond* pulse techniques in circuits associated with gas filled nuclear radiation detectors. Of course, the fast development of these techniques for radar and television during and after this war proved of great importance also to nuclear physics. When much faster types of detectors, such as scintillation and Čerenkov counters,—in which gas amplification is replaced by secondary emission amplification in a vacuum—came into use less than a decade ago, the existing techniques were quickly incorporated in the circuits associated with the new detectors, but they were soon found to be incapable of exploiting the very short time resolution that could be obtained with such counters. From the shops of the nuclear physicists themselves new techniques, which we now call *nanosecond* pulse techniques, then started to emerge. These were especially adapted to the new methods of detecting nuclear events. At the moment one may observe that such techniques are gaining importance even in other fields. Indeed, it seems that nuclear physics may give new impetus to the very fields from which it first derived its basic requirements in pulse technique.

In many cases, the distinction *nano*- vs. *micro*second techniques, implying a shortening of manageable time intervals by a factor of a thousand may seem a trifle ambitious: in quite a few circuits the improvement hardly exceeds a factor of ten—take for instance time resolution in fast scalers. Yet, ultimate time resolutions obtainable with scintillation counters may be better by a factor of one thousand as compared with counters that use gas amplification and therefore the term nanosecond techniques appears to be justified, if only to spur physicists on to improve further the nanominute or picohour resolutions obtained presently.

Why do we strive so after ever shorter time resolution? The answer is easy to find by looking at problems in nuclear physics that are fashionable right now. As an example, take lifetimes τ of very short lived nuclear levels. These may be determined by measuring the—statistically distributed—time intervals between the emission of particles exciting and de-exciting the levels, employing the well-known delayed coincidence technique. In the region $10^{-10}\,\mathrm{s} > \tau > 10^{-12}\,\mathrm{s}$ that can hardly be reached with presently available instruments, theory makes interesting predictions that we should like very much to verify. Another example is provided by the time of flight experiments with fast particles that are so rapidly gaining popularity and that are undoubtedly of special importance to many of you here. In this case better time resolution means better energy resolution. When such time of flight experiments are performed with a pulsed source—for instance a cyclotron, where phase bunching[1,2]) automatically gives pulsed operation, or a Van de Graaff or cascade generator in which the beam is swept across the

[1]) R. Grismore and W. C. Parkinson, Rev. Sci. Instr. 28 (1957) 245.

[2]) K. G. Malmfors, J. Kjellman and A. Nilsson, Nuclear Instruments 1 (1957) 186.

target[3])—delay fluctuations in the detector, and the finite width and possible jitter of the pulses from the source may decrease the obtainable resolution. As long as the particles from the source are strictly mono-energetic, the influence of these effects may in principle be reduced by increasing the length of the flight path, but in practice available intensities often limit flight paths to such lengths that the timing uncertainties form the chief limiting factors.

Of the factors that limit time resolution, some are of a fundamental physical nature—for instance the finite fluorescence decay time of luminescent materials in scintillation counters—others appear to be of a more technical nature—such as transit time spread in photomultipliers. In general, it may further be said that in quite a few cases phenomena in the radiation detector itself nowadays set limits of performance rather than the electronic circuits associated with it. This is clearly evidenced, for instance, by the improvement in performance of fast coincidence circuits when driven by artificial pulses instead of counter pulses. (By the way, this ought to show how misleading it can be to judge instrument performance with artificial pulses—though of course a source of such pulses can be extremely handy as a means of checking certain circuit characteristics quickly.)

In view of its primary importance we will therefore first look into factors affecting time resolution of fast radiation detectors. After that we will discuss some operations that may be carried out by fast circuits on the pulses these detectors produce, restricting ourselves here to methods for measuring short time intervals.

2. Time Resolution in Scintillation and Čerenkov Counters

In these counters a—mostly transparent—material, penetrated by rays or particles, becomes luminescent. As many photons as possible are collected from the phosphor on to the photocathode of a photomultiplier tube, where some of them liberate photo-electrons. These enter the secondary emitting dynode structure of the tube, starting avalanches of secondary electrons that result in sizeable current pulses at the anode.

The output pulses exhibit fluctuations both in *size* and *rise-time*. Suppose they are fed into a circuit that reacts as soon as they exceed a certain threshold value. Then, both size and rise-time spread will contribute to an apparent delay-spread in the circuit. Often the influence of fluctuations in size can be minimized by incorporating a pulse height selector that activates the instrument only when the pulses fall within a narrow predetermined pulse height interval. Therefore we will restrict ourselves here to rise-time fluctuations. Factors that influence rise-time are:

(1) fluctuations in delay of photon emission by the phosphor.

(2) fluctuations in the photon collection time, resulting from the finite size of the phosphor and possibly from a light guide between phosphor and photocathode.

(3) fluctuations in transit time of: (a) photo-electrons, (b) secondary electrons in the multiplier.

We will estimate first how factors (1) and (3) contribute to delay spread, neglecting (2) for the moment†.

In Čerenkov counters fluctuations of type (1) will only result from the finite time of flight of super-photic particles in the phosphor, the emission of Čerenkov light being instantaneous on passage of such particles. In general, such fluctuations will be negligible compared with those of type (2) and (3).

In scintillation counters, photon emission from the phosphor decays exponentially with time, and the decay rate may for our purposes be described by a single decay time τ. The average number of photo-electrons produced at the

[3]) W. Weber, C. W. Johnstone and L. Cranberg, Rev. Sci. Instr. **27** (1956) 166.

† Arguments similar to what follows have already been presented by Morton, Nucleonics, **10** (1952) 39. A more extensive treatment of scintillation counter statistics may be found in ref.[5]) and very recently in: S. Colombo, E. Gatti and M. Pignanelli, Nuovo Cimento, **5** (1957) 1739.

photomultiplier cathode within t seconds after excitation of the phosphor is then

$$n = m\,(1 - \exp(-t/\tau)) \approx m\,t/\tau \quad \text{if} \quad t \ll \tau \qquad (1)$$

m being the average total number of photo-electrons per scintillation.

The r.m.s.-deviation of the time of emission of the n–th photo-electron can be approximated by

$$\sigma_p \approx \tau\sqrt{n}/m \quad \text{if}\; t \ll \tau \quad (n \ll m)\;. \qquad (2)$$

Post and Schiff[4]) have given a more exact expression for σ_p, which is also valid if no longer $n \ll m$. It turns out that σ_p exceeds (2) increasingly as n/m approaches 1.

Expression (2) by itself would lead one to try and adjust the circuit associated with the scintillation counter so that it reacts already on pulse sizes corresponding to the emission of only one photo-electron. As we will see presently, this is justified only if other fluctuations may be neglected.

From (2) we also see that in order to minimize σ_p, the product of m—in which the luminescent efficiency of the scintillation enters—and $1/\tau$ should be as large as possible. This makes stilbene better suited to fast work than anthracene; an efficient plastic scintillator should be still better.

Turning now to time fluctuations in the photomultiplier we will designate as σ_i the r.m.s.-deviation of the time in which a single electron traverses the i–th stage of the multiplier (stage 1 is photo-cathode to 1st dynode, stage 2 1st to 2nd dynode etc.). The *average* time for n_i electrons to traverse stage i will then have r.m.s. deviation $\sigma_i/\sqrt{n_i}$ so that the r.m.s.-deviation of the total transit time through the multiplier will be

$$\sigma_t = (\sum \sigma_i^2/n_i)^{1/2}\;. \qquad (3)$$

Now let the circuit following the detector react as soon as the output pulse reaches an amplitude corresponding to an average of n_1 primary photo-electrons. If a be the amplification per stage, assumed equal for all stages and if $\sigma_2 = \sigma_3 \cdots = \sigma_n$ we may then write

$$\sigma_t^2 \approx [\sigma_1^2 + \sigma_2^2/(a-1)]/n_1 = \sigma_m^2/n_1\;. \qquad (4)$$

[4]) R. F. Post and L. I. Schiff, Phys. Rev. 80 (1950) 1113.

The combined effect of scintillator and photomultiplier is then given by the variance

$$\sigma^2 \approx \tau^2 n_1/m^2 + \sigma_m^2/n_1\;. \qquad (5)$$

This quantitiy can be minimized by taking $n_1 = \sigma_m m/\tau$, the minimum being

$$\sigma^2_{\min} \approx 2\tau\,\sigma_m/m\;. \qquad (6)$$

If σ_m were small compared with τ/m, this minimum would have no physical meaning since then n_1 would have to be much smaller than 1. In that case, $\sigma = \tau/m$ is the smallest realizeable value, as already shown by (2). In practice, $\sigma_m \gg \tau/m$ in most cases. Often, n_1 can be chosen so as to minimize (5). We have already remarked, however, that σ_p increases more rapidly with n_1 than suggested by (2) as soon as no longer $n \ll m$. A larger minimum than (6) is then found for $\sigma_{\min}$, reached for $n_1 < \sigma_m\, m/\tau$.

Minton[5]), to whom I owe much of the argument presented here, has measured a value $\sigma_m = 1.8 \times 10^{-9}$ s for an RCA type 5819 multiplier operated at an overall voltage of 1 600 V. This spread appears to be caused almost entirely in the photo-cathode to first dynode gap (across which 180 V was used). In a scintillation counter consisting of a 5819 with a stilbene crystal we would have to choose $n_1/m \approx 0.3$ to achieve $\sigma_{\min} \approx 2 \times 10^{-10}/\sqrt{E}$ (E in MeV). This follows from (6) assuming that 500 photo-electrons are produced per dissipated MeV in the crystal and taking $\tau = 6 \times 10^{-9}$ s for stilbene.

Special efforts have been made lately at RCA to minimize σ_m, and it has been reported that their latest photomultiplier, type 6810A, which has a concave photo-cathode, shows a marked reduction in the transit time difference of photo-electrons starting from different points on the photo-cathode as compared with the type 6810. The transit time spread of the 6810A may thus even approach that of the good old 1P21.

It should be remarked here that a time spread of about 1 ns in the photo-cathode—1st dynode stage at normal voltages remains in all

[5]) G. H. Minton, J. Res. Nat. Bur. Stand. 57 (1956) 119.

photomultipliers that have the photo-cathode at the inside of the glass, even when only a very small part of the photo-cathode is illuminated. This spread can not be explained just as an effect of initial velocities of the photo-electrons, these would cause much smaller fluctuations. As far as I know, no satisfactory explanation has been offered, perhaps we must think of straggling of photo-electrons in the cathode and/or secondaries in the 1st dynode.

Minton observes that in a 5819 σ_m is inversely proportional to the square root of the voltage across the photo-cathode to dynode gap. This suggests the use of high voltages across this gap; unfortunately breakdown phenomena may often prevent us from increasing this voltage as much as we would like. The use of high *overall* voltages is attractive too from other points of view: the amplification increases rapidly with voltage and space charge effects become less serious, resulting in a better linearity. With existing multipliers one should, however, beware of breakdown and fatigue, when voltages much in excess of the rated values are applied continuously. In pulsed operation, on the other hand, considerably higher overall voltages may be used without ill effects. Singer *et al.*[6]) report operating 931 A's satisfactorily at total voltages up to 6000 V, pulsing them on for 0.1 μs. Peak currents of the output pulses up to 15 A could be obtained and these pulses showed rise-times of about 1 ns. Thus, for extreme time resolution, pulsed operation of existing scintillation counters, for instance in combination with pulsed sources, appears very attractive. On the other hand, we should also urge tube manufacturers to try and increase continuously permissible voltages in photomultiplier tubes.

A few words now about fluctuations in the photon collection time, neglected thus far. If large scintillators are used, as in cosmic ray research, or if long light guides are necessary between scintillator and photo-cathode, a noticeable spread in the time of arrival of photons at the cathode will occur. Just as in the case of the finite decay time of luminescence in scintillation crystals we can again derive an expression for the r.m.s.-deviation σ_1 of the moment of production of the n–th photo-electron. For a simple light guide and if $n \ll m$ (m is again the total number of photo-electrons produced per scintillation) σ_1 is given by an expression obtained from (2) simply by replacing the decay time τ by the minimum time t_0 it takes a photon to travel from the spot where it is created to the photo-cathode ($\sigma_1 \sim t_0\sqrt{n}/m$). This means that fluctuations in photon collection time become comparable to those in photon production time in fast organic scintillators for light guide dimensions of the order of a foot.

3. Measurement of Nanosecond Time Intervals

Methods for measuring short time intervals between pulses from nuclear radiation detectors or between pulses from such detectors and a time reference pulse source find many applications in nuclear and meson physics. In the last few years some interesting new techniques have been developed for measuring time intervals in the nanosecond region. Effort has been directed at coding time difference information in such a way that it can be handled by multi-channel storage devices. A much used method of coding is time to pulse height conversion, in which case a multi-channel pulse height analyzer can be used to store the information. In the following, some methods for measuring nanosecond time intervals will be surveyed. We will start with

3.1. CONVENTIONAL FAST COINCIDENCE CIRCUITS

Some of the most used circuits of this type are actually Rossi-circuits, to which a very non-linear element, mostly a crystal diode, has been added to improve coincidence discrimination. A general requirement of the Rossi-circuit is that a number of current paths leading to a common point must be completely blocked. If vacuum tubes are used in these paths negative pulses of at least a few volts are needed to achieve this. A very familiar version of this

[6]) S. Singer, L. K. Neher and R. A. Ruehle, Rev. Sci. Instr. 27 (1956) 40.

type of circuit is that introduced by Bell *et al.*[7]). In view of a modification of its operation to be discussed a little later I want to repeat here how it works. Negative pulses from two scintillation counters block limiter stages that deliver equalized positive pulses through delay cables to a common shorted shaping stub. To the input of this stub a crystal diode is connected, acting as a coincidence discriminator. This will conduct only if pulses from both channels overlap. The coincidences thus passed by the diode are then amplified and finally fed into a second discriminator, the setting of which determines the amount of overlap required to produce a coincidence count at the output of the unit. Time difference between counter signals is measured as the extra length of delay cable in one of the channels needed to bring the pulses in coincidence.

Some of the other conventional circuits in use for fast coincidence work have the advantage that they require no pulse equalization and will work satisfactorily with input pulses of only a few tenths of a volt. With the new photomultipliers, such as RCA's 6810A, pulse heights of a few volts are, however, easily realized, even for weak scintillations, Therefore, Rossi-type circuits such as Bell's and also Garwin's can be made to operate satisfactorily in most cases.

There may as yet be a special case for the so called

3.2. DIFFERENTIAL COINCIDENCE CIRCUITS

as introduced by Bay[8]) and also used by Minton[5]). The principle of differential coincidence operation is as follows: in conventional coincidence circuits there is an overlap region of the pulses at the coincidence mixer proportional to their widths. Since coincidences may also be passed when the overlap is not complete the coincidence curve will show a broadening dependent on pulse width and second discriminator setting. In a differential coincidence circuit events with incomplete overlap are rejected so that the width of the coincidence curve becomes almost exclusively determined by delay fluctuations in the multiplier.

It seems that *in principle* differential operation does not offer special advantages for obtaining ultimate time resolution, since also with a conventional circuit, e.g. Bell's, the width of the coincidence curve can be narrowed by using high first and/or second discriminator bias, and it appears that comparable widths are obtained at comparable coincidence efficiencies. It is possible, however, that better stability can be obtained with a differential coincidence circuit than with a conventional one set at high discriminator bias.

We will pass now to methods embodying *time to pulse height conversion* (3.3–3.5).

3.3. ACCUMULATED CHARGE METHOD

A very straightforward method of this kind consists of switching on a constant current that charges a capacitance each time at the beginning of a time interval to be measured and switching it off again at the end. The voltage pulses thus developed across this capacitance (C) will have amplitudes proportional to the width of the time intervals to be measured, they are fed into a pulse height analyzer. A

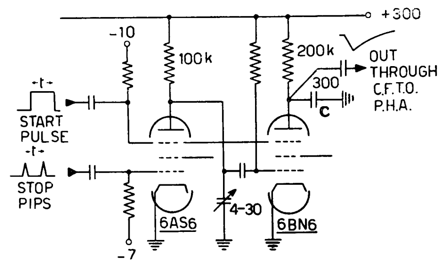

Fig. 1. Straightforward time to pulse height converter (ref. [3])).

circuit for measurements of time intervals in the nanosecond region in which this principle is employed, due to Weber, Johnstone and Cranberg[3]) is shown in fig. 1. It is used in a neutron time of flight spectrometer. The neutrons are produced in 2 ns bursts by a Van de Graaff generator in which a proton beam is

[7]) R. E. Bell, R. L. Graham and H. E. Petch, Can. J. Phys. 30 (1952) 35.
[8]) Z. Bay, Phys. Rev. 83 (1951) 242.

swept across a target. Pulses from the neutron detector are fed into a discriminator-pulse former which delivers the start pulses that initiate the charging of C by switching on the anode current of the 6BN6. These pulses have a width (t = 270 nsec) equal to the distance between neutron bursts. Stop pips, derived from the Van de Graaff beam deflection arrangement are fed to the first grid of the 6AS6 coincidence tube. The first pip that arrives after a start pulse will cause the 6BN6 to be cut off at its first grid. Capacitive stretching of the coincidence pulse at the 6AS6 anode prevents the 6BN6 from conducting until well after the start pulse has ended. Good time to height conversion linearity has been achieved except when stop pips arrive too near the edges of a start pulse. The authors state that the precision of time measurements is limited only by the characteristics of the detector. It seems, however, that these characteristics may affect the obtainable resolution rather seriously in this case as a result of time jitter caused by the amplitude spread of the neutron pulses in the discriminator pulse former.

3.4. OVERLAP TO CHARGE CONVERSION

A second, rather straightforward method of time to pulse height conversion has recently been mentioned by Sunyar[9]) (and it has apparently been used already some time ago in Chalk River). It uses Bell's coincidence circuit, just described. In this circuit, the charge passed by the discriminator diode when two pulses overlap at its input apparently is a measure for the degree of overlap, and therefore of the relative delay of the pulses. The output pulse height distribution of the rather slow amplifier that follows the diode reflects the charge distribution of the pulses passed through the diode and therefore also the delay distribution of the pulses from the detectors that fall within a time interval equal to the width of the shaped pulses. It is clear that really well equalized pulses are needed, since any size fluctuations will appear as delay fluctuations.

[9]) A. W. Sunyar, Bull. Am. Phys. Soc. **2** (1957) 137.

3.5. VERNIER METHODS

We now turn to the intriguing *vernier principle of time magnification*, introduced by Cottini, Gatti and Giannelli[10]). Since Dr. Gatti will say more about this I want to confine myself to mentioning the basic principle here and say a few words about statistics.

Pulses from two counters shock excite two LC-circuits tuned to slightly different frequencies (ω_1 and ω_2). Wave trains from these tuned circuits are mixed in a ring modulator, at the output of which the frequency difference $\omega_1 - \omega_2$ appears. Since the phase angle of the difference frequency is equal to the initial difference of the phase angles of the wave trains, a relative time shift of the wave trains by t seconds corresponds to a time shift $T = t\omega_1/(\omega_1 - \omega_2)$ of the difference frequency wave. Since T/t may easily be of the order 100 the shift T can readily be measured by a conventional time-to-height converting method.

As has been pointed out by Cottini and Gatti[11]) the phase of the shock excited wave trains is determined by the position of the centroid of the exciting pulses, provided these are short compared with the period of the wave. Therefore, the phase is independent of the amplitude of the pulses, at least as long as the circuit preceding the point where the shock waves are excited has a linear response. This is a very definite advantage of the vernier method.

The centroid of the pulses exhibits fluctuations in time as a result of finite phosphor decay time and transit time spread. We may approximate the variance of the total time spread by

$$\sigma^2 = \frac{\tau\sigma_m}{m}\,(\tau/\sigma_m + \sigma_m/\tau) \tag{7}$$

which may be compared with eq. (6). It is seen from this comparison that σ approaches the value $\sigma_{\min}$ obtained in paragraph 2 if $\sigma_m \approx \tau$. This latter condition has indeed been realized by Cottini and Gatti, by using a scintillation phosphor with $\tau = 3 \times 10^{-9}$ s, they assume $\sigma_m = 2.10^{-9}$ s.

[10]) C. Cottini, E. Gatti and Giannelli, Nuovo Cimento **4** (1956) 156.

[11]) C. Cottini and E. Gatti, Nuovo Cimento **4** (1956) 1550.

The vernier method has also been adapted to time of flight neutron spectroscopy by Chase and Higinbotham[12]). In their instrument the wave-train from one of the detectors is replaced by a continuous wave derived from the r.f.-oscillator of a phase bunching cyclotron. This method has the advantage over the straightforward method mentioned under 3 of this paragraph that only a very small part of the r.f. cycle is lost for time analysis, even though the frequency is quite a bit higher (20 Mc/s in Chase and Highinbothams case).

A more literal version of a vernier method has been devised by Lefevre and Russell[13]). They describe a vernier chronotron, in which pulses from two detectors are placed on two circulating lines (fig. 2) of slightly different length. Each

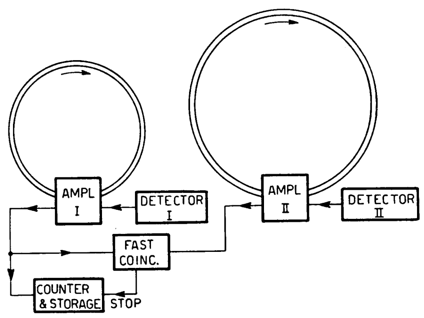

Fig. 2. Vernier chronotron (tentative block diagram, according to ref. [16])).

time after going round the line, the pulses are passed through saturating amplifiers. After a number of revolutions equal to the initial distance of the pulses divided by the delay difference of the lines they coincide. The coincidence pulse stops an address which had started counting when the first pulse arrived. Finally a pulse is added in the channel of the storage device at which the address had stopped. (Since only a cursory note in the Bulletin Am. Phys. Soc. about this instrument was available, part of the operation of this system is guessed.)

3.6. OSCILLOGRAPHIC METHODS

Time difference measuring devices should be mentioned in which use is made of an oscilloscope. The conventional oscillographic method is, of course, the photographic recording of properly triggered fast oscilloscope traces on which the pulses of which we wish to measure the distance appear. Because the whole detector pulse is displayed on the screen we can determine its position at least as accurately with this as with any of the other methods described so far. With modern travelling-wave oscilloscopes pulse intervals down to a few nanoseconds can be separated very well.

3.7. CHRONOTRONS

A last method to be briefly mentioned is the chronotron the principle of which is indicated in fig. 3. Pulses from two radiation detectors enter a fast line from opposite ends. Coincidence discriminators, distributed along this line, produce output pulses, the amplitude of which depends on the degree of overlap of the pulses at their inputs. These outputs are fed into a common slow line (also, a separate line for each detector can be used) and arrive at its right hand terminal with intervals of, for instance, 0.5 μs. This row of pulses can be displayed on an oscilloscope. From the pattern on the scope the relative delay of the pulses from the radiation detector can be determined. Ticho and Gauger[14]) describe a chronotron with a range of 20 ns and report a timing precision of $\pm$ 0.18 ns, using 5819 multipliers looking into liquid scintillators

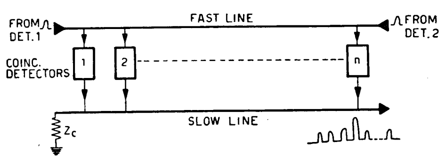

Fig. 3. Principle of chronotron.

traversed by cosmic rays. This precision indicates that the time resolution of the scintillation counters is the chief limiting factor also here.

[12]) R. L. Chase and W. A. Higinbotham, Rev. Sci. Instr. 28 (1957) 448.

[13]) H. W. Lefevre and J. T. Russell, Bull. Am. Phys. Soc. 2 (1957) 175.

[14]) H. K. Ticho and J. Gauger, Rev. Sci. Instr. 27 (1956) 354.

4. Conclusion

In almost any well designed instrument for measuring time intervals between pulses from scintillation- or Čerenkov-counters, the timing precision is limited by fluctuations in the detector. These are caused for an important part by transit-time spread in the photo-multiplier, as is revealed by a statistical analysis of the processes in the counter. It is to be hoped that photo-multiplier tubes with a further reduced transit-time spread will become available. At the moment their appears to be no fundamental reason why such tubes cannot be made.

DISCUSSION

GATTI pointed out that in the analysis it was the n–th electron which started the time measurement, whereas one really makes an average with different weights for the different photo-electrons.

DE WAARD agreed with this but said he wanted to get a lower limit.

BISHOP asked what was the minimum value of σ_1, and suggested that there were two possible contributions—one is the varying electron path lengths, while the other might be in the secondary emission process itself. DE WAARD thought this latter was normally considered small. There is also the possibility of straggling of photo electrons. Electrons can exist in the cathode for a finite time before combining. BISHOP pointed out that electrons penetrate to different depths according to the velocity and angle of approach, before they arrive at the surface and give rise to secondary electrons. This might give an ultimate limitation on σ_1.

VON DARDEL said that while Clyde Wiegand was at CERN he gave the latest information on the new R.C.A. photomultipliers. Apart from the 6810 A which has a curved inner surface, there is in development one with a curved inner and outer surface to reduce the straggling of electrons from different parts of the cathode to within 0.2 ns. The accelerating structure is the same, so σ_1 will remain the same. Dr. Morton at R.C.A. is attempting to put high potential grids between the dynodes to give a high field on the electrons when they come out of the dynodes, and this decreases the transit time through the linear structure by a factor of about 10. These improvements will give a factor 10 improvement on σ_1.

GATTI said that Dr. Bey of the Bureau of Standards suggested to him in a private communication just this idea of the grids, and in particular one very near to the cathode. It is not so very important to reduce straggling time in the later stages when there are many electrons, but it is important to have a low straggling time when the first electron is involved.

MOODY commented on the use of diodes in the Fast Coincidence Circuit and the assumption that the characteristics are linear with time—and pointed out that this is not true because the impedance of semi-conducted diodes is a function of time. These effects apparently do not entirely stop one from doing these things because he did them some seven or eight years ago, almost in ignorance of the effects. The characteristics of diodes are now well known and they have been measured—one should not neglect them when using diodes for fast pulse work.

DE WAARD asked if there had not been a considerable improvement in diode characteristics since then.

MOODY said it was difficult to give a quantitiative answer since there are so many parameters and diode types; the best turn off time is about a 10 to 1 fall in current in 0.03 μs. But it is easy to find diodes with 0.1 μs fall time and even higher. Turn on time will be of the order of 0.01 μs. Such good diodes usually are characterised by a high forward current at quite a low voltage, and an inability to withstand a reverse voltage of more than 10 volt.